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Liquefied petroleum gas (LPG) as a medium-term option in the transition to sustainable fuels and transport

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ABSTRACT

Undoubtedly, the changes spark ignition engines (hereinafter SI engines, Otto engines) have undergone under the last 20–25 years has been due to pressure from emission standards and fuel economy requirements becoming ever stricter. These regulations have equally influenced the every stage (from 1st to 5th generation) of LPG technology development while looking back in retrospective. Increasing emphasis on liquefied petroleum gas (LPG) as a clean, relatively low in cost and abundant energy source to provide affordable fuel-efficient transportation, encourages the search for the optimum approach to management of fuel, air and combustion to achieve the best results in vehicle power, fuel efficiency and low gaseous waste products. The development undertaken since then is still a “work in progress” leading to the course of establishing the new systems, including those for Otto engines with direct gaseous fuel injection as well as direct liquid LPG injection.

In performing the analysis of LPG fuel systems (the 1st, 2nd, 3rd, 4th, and 5th) for internal combustion engines (ICEs), special emphasis is put upon the thorough examination of their structural control diagrams. The critical review also provides a detailed description of characteristics and classification of fossil derived gases (LPG, CNG, and LNG) as fuels in motor vehicles, discusses different types of existing LPG fuel delivery systems and requirements to gas equipment, and presents a thorough analysis of the SI engine operation using LPG as a fuel.

Contents

1. Introduction

Never ending discussions regarding the amount of oil supplies, its uneven distribution, stiffening ecological requirements stimulate more persistent use of cleaner combusting alternatives to conventional liquid automobile fuels: liquefied petroleum gas (LPG) [1–5], compressed natural gas (CNG) [2,4,6–10], and liquefied natural gas (LNG) [2,11,12]. Because of less availability, land use competition

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and/or underdeveloped technologies liquid biofuels, fuel cells and hydrogen, currently can only replace fossil fuels to a very limited extent even if compared to LPG [13–15], hence they are not discussed in this paper. In Europe, LPG propels **7** million passenger cars thus being the most widely used alternative fuel that offers a series of specific advantages. Propane's particular characteristics make it ideally suited to the contemporary energy-economy–ecology development tendency, in which Europe faces the challenge of balancing the diverse imperatives of security, sustainability and competitiveness [15]. The use of this type of fuel is pre-conditioned by its low price, highly developed supply system and relatively unsophisticated adjustment of engines [1,2]. As an environmentally friendly and economic fuel, liquefied petroleum gas can help keep planetary citizens moving while minimizing the impact of road transport on climate, weather, natural resources, and the human health [15]. Different attributes contribute to make it a progressive alternative as part of a diverse and sustainable transport energy mix. Due to its heterogeneous emergence and development, the EU-27's liquefied petroleum gas market remains fragmented and characterized by a high level of untapped potential [15]. Successful development in a number of national markets, both in Europe and around the globe, demonstrates that given the necessary commitment on the part of the sector and public policymakers, LPG can emerge as a key element of the energy portfolio for the road transport sector, yielding considerable socio-economic and environmental benefits [15].

However, the use of LPG requires more detailed investigation of the characteristics of this alternative fuel and the particularities of its use [1]. The majority of car engines run on gas have been designed to run on petrol. Due to this reason, in order to adjust the engine properly to run on petrol substitute certain difficulties arise. Different internal combustion engines (ICEs) used in cars are characterized by individual properties therefore there are no gas equipment systems ideally suitable for each engine yet. While using LPG there are always problems present, such as power losses, adjustment of the composition of exhaust gases, etc [1,16–20]. Very few scientific studies have been devoted to details of this issue [1,2,17–20]; with the possible exception in Ref. [16], there are practically no control algorithms for fuel gas delivery systems being described in detail. Most of the problems are created by improper adjustment of gas equipment or inappropriate selection of the equipment for an individual engine [1,21].

As far as LPG is concerned the most acute problems discussed are the environmental ones, especially in bigger towns or cities. It is alleged that liquefied petroleum gas is much more ecological fuel compared to petrol as it produces less toxic combustion products and that there are no heavy metals present in LPG [21,22]. It is also alleged that in order to reduce the ever increasing pollution in big cities liquefied petroleum gas should be used and the results will be fairly good [23]. Therefore, it is obvious that an internal combustion engines run on LPG can function in an optimal mode only after having adjusted all the systems of engine and gas equipment properly [1].

2. Characteristics and properties of natural gas and liquified petroleum gas

2.1. Compressed natural gas (CNG)

Although the first successful attempts to use gas as a fuel for engines were made at the end of the 19th century [24,25], the first factory manufactured engines run on CNG emerged nearly seven decades ago in the former Soviet Union (in 1950s) [24] and later in the USA (in 1960s) [1]; most commonly they were used in vehicles. Russian automotive historians date use of gas as an engine fuel in the country from 1936, when the Resolution of the Soviet of People's Commissars of the USSR on gasification of road transport was issued [24]. In 1939, the Scientific Automobile and Automobile Engine Institute (NAMI) created the compressed gas vehicles ZIS-30 (Zavod imeni Likhachova) and GAZ-44 (Gorky Automobile Plant) running on liquefied petroleum gas. Soon afterwards, that same year, the first natural gas vehicles refueling compressor stations were constructed in Moscow (Russia), Melitopol (Ukraine) and Gorlovka (Ukraine) [24]. In the 1950s, the compressed gas vehicles GAZ-51B and ZIS-156, running on compressed natural gas, were designed and brought into production [24]. In 1992 Cummins L10-240 G engine was designed, manufactured and certified and it appeared on the US market as a natural gas engine for vehicles. Presently the most vehicles run on CNG are used in the USA [26,27].

CNG is usually stored in high pressure containers at a pressure of 20–32 MPa [28]. All appliances designed to store or transport CNG have to withstand 1.5–4.0 times higher pressure compared to the nominal gas pressure [29]; in addition, specific criteria for natural fuel gas have to be established, mandatory for fittings, valves, hoses, controllers and filters. Accordingly, metal alloys, plastics, galvanized aluminum and copper alloys with over 70 percent of copper are not suitable to be used in servicing natural fuel gas due to insufficient hardness and resistance to corrosion which is essential in using CNG. The main material for CNG pipelines and components is stainless steel as water and sulfite admixtures, which can be present in CNG, are of corrosive nature. Huge stationary CNG storage tanks for fuel filling are usually made of steel and classified according to the standards and requirements set by technical supervision services (TSS) [30]. According to TSS standard, these pressure vessels are used up to 32.7 MPa pressure [1]. Fire protection is the main criterion in planning any new CNG fuel filling station. Special precautionary measures are applied to prevent compressor oils enter the CNG systems of vehicles.

CNG operation is specific in itself. Natural gas differs from other fuels by fast ignition. It is especially flammable when its concentration in the air reaches 5–15 percent (by volume) [31], therefore, any leak of natural gas is considered to pose a fire hazard as a combustible gas-air mixture is formed. Compressed natural gas is lighter than air and it rises upwards from the spot of leakage. A minor leakage of CNG can be noticed only by smell or using a methane detector. Specific techniques of fight against fire are applied in the case of compressed natural gas. To extinguish the flame efficiently only powder and CO_2 fire extinguishers are appropriate. In the USA the majority of vehicles running on CNG have automatic fire extinguishing systems installed, however, it increases the price of the equipment [1]. Besides fire hazard another important danger criterion is a high pressure hazard. Due to gaseous nature of CNG and to the fact that it is stored highly compressed its features of use differ greatly from those of liquid fuel and its filling procedures must be strictly recorded. Quite often the procedure of fuel filling differs depending on the location of a filling station [26,27,29].

In fact, routine service operations for CNG vehicles do not differ from traditional vehicles. However, high pressure of gas, changes of density caused by changing temperature and other specific properties require additional specialized service procedures carried out for CNG vehicles. Due to leakage risk all valves of a CNG system have to be blocked and the fuel system pressure lowered before performing any CNG vehicle service operation at a service station. Heating sources, i.e. space heaters can ignite the leaked out gas. In order to avoid dangerous gas accumulations additional ventilation is necessary [1].

Locating CNG tanks in vehicles is a sore problem as they must be round and have to be installed only in certain spots. CNG tanks for cars are made of steel or aluminum with filament windings like

glass fiber/aramid or carbon fiber around the metal cylinder [1]. These tanks are designed to withstand the pressure of 20–24 MPa. Compared to petrol tanks CNG tanks are heavier and reduce the mass of cargo transported in the vehicles. The cylinders made of composite materials are lighter. In the USA CNG pressure vessels used in vehicles are made of reinforced aluminum which reduces the cargo mass by 12 percent compared with diesel or petrol vehicles. The cargo mass in vehicles with steel cylinders can be reduced down to 40 percent [1].

As the efficiency of compressed natural gas engines is lower than that of diesel engines CNG engines consume 15–25% more fuel [1,22,27]. The gas filling system is expensive and usually requires huge investments which are expected to recover by selling more and more of the fuel of this type or by increasing its price. The duration of fuel filling is also a very important criterion when using CNG. The analysis of CNG fuel filing stations in the USA (such as LACMTA Sun Valley and SRTD) shown [32] that the fuel filling duration can be rather short (about 4 min). The disadvantage of fast-filling is that with an increase of temperature gas density lowers and the density of the gas filled is about 18–26% lower than that of the gas filled by a slow method [1,27,32]. The duration of slow filling depending of the compressor capacity and the number of vehicles serviced can vary from 30 min to 10 h [32].

2.2. *Liquefied petroleum gas (LPG)*

LPG (also known as "Autogas") is a gas product of petroleum refining primarily consisting of Propane, some propylene, Butane and other light hydrocarbons. Petroleum gas at the pump is in the gas state, however most commonly it is used liquefied by pressure. Propane is the most common type of fuel for internal combustion engines after petrol and diesel [1,18]. The composition of LPG can be found in many mixtures raging from pure Propane through various ratios of Butane and Propane to pure Butane (see Table 1).

At a very limited scale, liquefied petroleum gas has been used as a fuel for vehicles as early as 1912. Initially, gaseous fuels have been used for internal combustion engines as "designated" fuels. LPG became more popular since the mid-1950s when the widespread take up of "dual-fuel" engine technologies came to transport [35]. Dual-fuel vehicles have two separate fuel systems, with only one fuel being used at a time; this allow LPG to be used in parallel with other fuels (petrol or diesel).

LPG is suitable as a fuel for ICEs, the Octane number of which is close to 105, therefore, cars and medium/heavy-duty vehicles have been using Propane or Propane/Butane mixtures successfully [2]. Many researchers propose that autogas has a potential of reducing NO_x and hydrocarbon emissions substantially and there are very few harmful metal compounds compared with petrol or diesel [36–40]. Due to a low amount of sulfide when using LPG fuel engine wear and tear is also reduced [1]. Certain researchers have carried out investigations with ICE run on LPG and established that motor oil changing periods have elongated [22]. It is also proposed that diesel engines run on LPG do not produce smoke and the exhaust gases have no odor. Different authors [1,22] argue that LPG engine can be easily started at an outdoor temperature of $-7\,^{\circ}C$.

Liquefied petroleum gas is stored in cylinders (vessels of moderate pressure), in a liquid form, compressed by about 760–1030 kPa pressure [1]. LPG fuel cylinders are made of carbon steel and design-wise they are very similar to compressed air cylinders. The working pressure in car pressure vessels is about 2.2 MPa. Cylinders can be manufactured in different sizes to have a possibility to adjust them in different vehicles.

LPG vehicles require the same daily maintenance as diesel or petrol vehicles. The duration of fuel filling of a vehicle is close to that of petrol or diesel fuel. There can be some difficulties when installing LPG pressure vessels in cars – similar to those when using CNG – however, in this case the cylinders are of a lesser capacity and pressure, and therefore, it is easier to adapt them in cars. Unfortunately, LPG pressure vessels are larger and heavier compared to diesel or petrol fuel tanks of analogous energy capacity due to two reasons (i) LPG has a lower energy density than either diesel fuel or petrol, so fuel gas tanks are designed for a somewhat larger volume of LPG needed to drive the similar distance; and (ii) LPG pressure vessels are filled only to 80% of the overall capacity.

The requirements for the materials used in LPG equipment are very close to those applied to CNG. Safety and fire extinguishing regulations as well as possible dangers described in [41–43] are similar as well, however, LPG is heavier than air, therefore, a specific characteristic has to be emphasized that in case of a leakage gas and air mixture is accumulated in the lowest places [1]. In addition, during the filling of LPG to a vehicle there is always a leakage to the atmosphere while disconnecting the filling connectors. Consequently, according to the regulations regarding LPG composition chemicals of specific odor are added to indicate leakage [41]. Specific odor is mandatory for all types of LPG [44,45].

There are already signs that Otto cycle spark ignition petrol and LPG engines are regaining lost ground on fuel economy and drivability [46]. Only a few years ago, most of Europe's smallest vehicles could be bought with diesel engines in sizes as small as 1.0 l. Today, they are starting to disappear, replaced by small-capacity, turbocharged petrol engines [46]. With ever tightening emissions requirements, it may simply get too expensive to make diesel engines worthwhile for economy-conscious buyers [47]. Volkswagen has officially declared it will not make any future diesels of less than 1.6 l [46]. Moreover, while assessing the costs of installing LPG equipment in a car one should take account of the fact that petrol cars are normally a cheaper than their diesel counterparts [1]. The same trend is observed in both buying a new car or the pre-owned vehicle. It is mainly due to the high cost of the after-treatment system (for small cars especially), more complex fuel system, and more frequent and costly service required [1]. That means, the difference in vehicle price should cover the LPG equipment installation costs completely in both cases. As the efficiency of LPG engines is 10–15% lower (when it is

Table 1
Physico-chemical property data for butane, propane and butane/propane mix (LPG).

Characteristics	Butane [33,34]	Propane [33,34]	LPG [1]
Chemical formula	C_4H_{10}	C_3H_8	Mix. of mainly 40% C_3H_8 and 60% C_4H_{10}
Burning velocity (cm/sec)	32 in air	32 in air	32 in air
Molecular weight	58	44	50
Specific weight (Kg/l)	0.580	0.510	0.54
Boiling point (°C)	−0.5	−43	−0.5–43
Lower heating value (Kcal/Kg)	10920	11070	10997
Fire point (°C)	490 atm	510 atm	~500 atm
Ignition limits (% of volume)	1.5–8.5	2.1–9.5	1.5–9.5

operating at its optimal range) than that of diesel engines, LPG engines consume about 35–50% more fuel compared with the diesel ones of the analogous capacity [1]. While taking into consideration the fact that LPG price during the last five years is ranging at 45–62% of a petrol price we conclude that LPG prices are somewhat similar to those of diesel in terms of energy equivalent [1].

The major drawback for liquefied petroleum gas is its limited availability in different countries; it could not be other than a niche fuel for some North American and European countries, etc [1,2]. For several years in a row, the world leader in number of LPG-powered vehicles per country is Democratic Republic of Armenia where about 20–30% of cars run on autogas [48].

2.3. Liquefied natural gas (LNG)

LNG is produced by cooling natural gas and purifying it to the required amount of methane achieved. Liquefied natural gas is stored in a compressed state in the tanks of moderate isolation at a temperature down to −165 °C [49]. It is a relatively new type of fuel used as an alternative fuel for vehicles. The majority of projects and investigations related with this fuel as with CNG are carried out in the USA [1].

Cooled down and liquefied natural gas is distinguished for intermediate characteristics between CNG and LPG. Contrary to CNG, high pressure is not required to store LNG in a liquefied form at a low temperature. In the case of leakage, depending on a temperature, LNG vapour can be heavier or lighter than air therefore the vapour leaked out from LNG tanks can accumulate in the upper as well as in the lower part of premises [1].

If we take into account gas preparation (cooling) time, the duration of car filling by LNG is longer if compared with petrol, diesel or LPG. However the very filling process takes more or less the same time as with above mentioned types of fuel. At present the problems to be solved are: the longevity of LNG equipment, difficulties in storing cooled down LNG in its liquid state in tanks, and the problems of potential change in composition during LNG storage related with the instability of heavy hydrocarbons [1]. The changes of composition are directly related with the purity of methane reached during LNG production. The main difference between the LNG vehicles and the cars using other types of fuel is that, if the LNG vehicle is not used for a long period of time, it is necessary to empty its gas cylinder completely [1]. The existing designs of tanks allow keeping LNG for 8–21 day periods during which the gas has to be used.

To compare the types of alternative fuel (CNG, LPG, LNG) their summarized characteristics and properties based on the scientific literature analyzed are given in Table 2.

LPG, CNG, and LNG have higher octane number than gasoline. It allows engines running on LPG/CNG/LNG to have higher compression ratios, and thus higher energy efficiencies, than Otto cycle engine. The higher heating value of LPG is 46.23 MJ/kg. Low carbon build-up and oil contamination characteristics of liquefied petroleum gas and its high Octane rating result in a longer engine lifetime (life of some components such as piston rings, bearings, etc.), up to twice that of the spark ignition engines [51]. Typical performance and cost figures for retrofit LPG/CNG/LNG cars are summarized in Table 2. In terms of future cost projections, retrofit costs (Euro/Otto engine) for small/medium/large cars LPG and natural gas technologies will continue to experience price reductions with economies of scale and technological development [51]. However, modern technologies are relatively advanced and therefore will experience only a limited decrease in cost in the next years to come. Base energy consumption (KJ/km) and operation/maintenance costs (Euro/km) for small/medium/large cars, in principle, do not differ significantly from either fuel type. As seen

Table 2
Properties of CNG, LPG and LNG and features of their use.

Characteristics	CNG [1,2,8,9,18,26,28–30,33,50,51]	LPG [1,2,17–22,26,33–35,37,38,41,45,49–51]	LNG [1,2,11,12,26,31,33,49–51]
Energy content	37–40 MJ/m^3	25.4 MJ/l	25 MJ/l
Octane number	120	92–110	120
Higher heating value	46–49 MJ/kg	46.23 MJ/kg	45.5 MJ/kg
Storage	High pressure vessels (up to 34.5 MPa)	Cooled (−50 °C) [41] moderate pressure tanks (up to 2.6 MPa)	Cooled (−165 °C) [41] moderate pressure tanks (up to 1.1 MPa)
Filling a fuel tank	Special connector for high pressure fuel	Special fuel connector	Special connector for cooled down fuel
Vapour recovery	Not applicable	Desirable	Necessary
Danger of being nearby	• Physically dangerous due to high pressure; • Can cause injuries or embolism	• Physically dangerous due to pressure; • Can cause injuries or embolism; • Hidden vapour heat can freeze body tissues.	• Especially physically dangerous due to low temperature; • Direct physical contact with the very fuel or equipment can cause deep frostbites.
Risk of fire	• Released gas is lighter than air; • Ignites much easier than diesel.	• Vapour lighter than air; • Ignites much easier than diesel	• Vapour lighter than air; • Ignites much easier than diesel
Facilitation of fire prevention	Ventilation and/or explosion resistant equipment at ceiling level or in a pit	Ventilation and/or explosion resistant equipment at floor level and in a pit	• Ventilation and/or explosion resistant equipment at ceiling level or in a pit; • Ethane detectors are desirable as gas has no odor.
Automatic fire extinguishing	Desirable	Desirable	Desirable
Output costs compared with diesel	Much higher compared to diesel	Moderately higher compared to diesel	Much higher compared to diesel
Operation costs compared with diesel	Similar to those of diesel	Similar to those of diesel	Similar to those of diesel
Retrofit cost (Euro/Otto engine) for small/medium/large cars [50,51]	1640–2190/N/A/N/A	1130/1130–1528/2740	1640–2190/N/A/N/A
Operation and maintenance costs (Euro/km) for small/medium/large cars [50,51]	0.03/0.04/0.05	0.03/0.04/0.05	0.03/0.04/0.05
Base energy consumption (KJ/km) for small/medium/large cars [50,51]	2.2/2.6/4.1	2.3/2.7/4.1	2.2/2.6/4.1
GHG emissions (g/km)) for small/medium/large cars [50,51]	93.3/108.3/165.7	122/141.7/216.7	93.3/108.3/165.7

in Table 2, the use of CNG and LNG instead of LPG improve the GHG emissions considerably.

3. Types of LPG fuel delivery systems, requirements to gas equipment

A functional scheme of the vehicle gas delivery system (GDS) is presented in Fig. 1. GDS can be relatively divided into three blocks. The first one is the LPG tank equipped with filling and safeguard systems (automatic fill limiter, excess-flow valve, non-return valve (check valve), pressure relief valve (safety relief valve), etc.). All the components comprising the first block are connected to the GDS by the non-return valve that permits the gas flow in only one direction and prevent the flow in the opposition direction. Auto LPG fuel cylinders are fitted with a valve that stops the flow once the cylinder has reached its maximum safe filling level. An automatic fill limiter is a device installed in the liquefied petroleum gas fuel cylinder, which should automatically terminate filling when a predetermined 85% level in the fuel cylinder is reached. It ensures sufficient vapour space for expansion of LPG [1,52]. Filling should be shut off before the maximum permitted filling level is exceeded. As reported in Ref. [52], an excess flow valve is usually installed at the outlet connection of the LPG fuel tank. It is normally in open position and should close automatically when the flow in a specified direction exceeds a predetermined limit under abnormal conditions to protect against leakage of liquefied petroleum gas [52]. The second block of GDS describes the process of fuel mixture preparation and the third one – processes of fuel delivery, gas/air mixture formation and injection control.

The LPG tanks used in cars can be classified according to two main criteria (see Fig. 2): (i) type of supporting (filling and safeguard) system, and (ii) physical characteristics (shape, capacity, weight) [1]. According to criterion (i) we can distinguish three

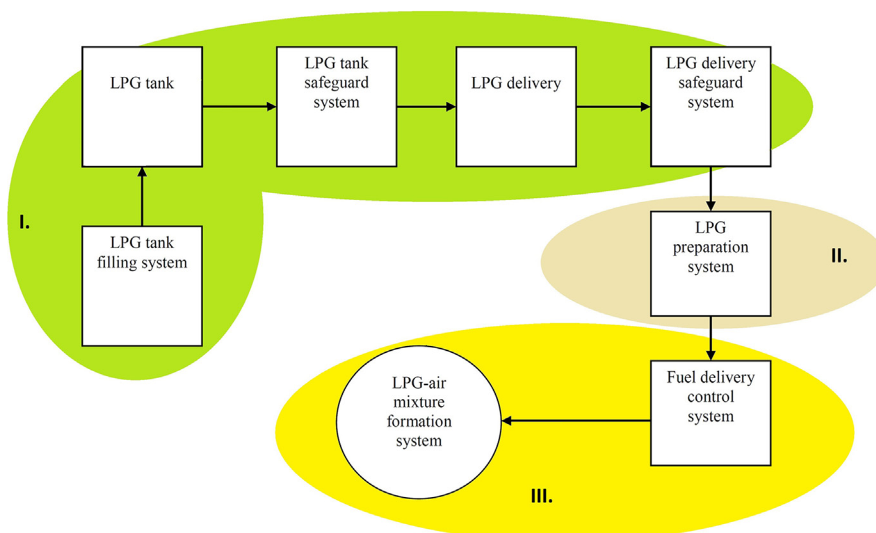

Fig. 1. Functional diagram of LPG fuel delivery system [1].

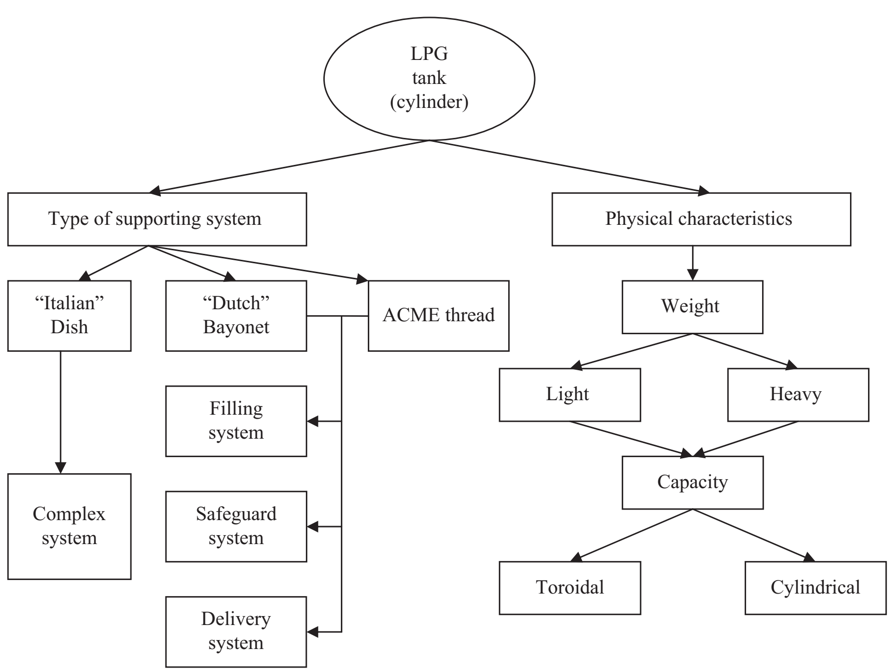

Fig. 2. Flow chart for the classification of LPG tanks [1].

Fig. 3. LPG tank patterns.

different types: the "Italian" Dish type where a safeguard system is used to perform several functions, like safeguarding, filling and fuel delivery at the same time (Complex system), the "Dutch" Bayonet type where these functions are performed by different devices, and ACME thread type whose principle of operation is similar to that of the "Dutch" Bayonet type. It should be noted that "Italian" Dish propane adapters are available that allows a vehicle fitted with a particular system to refuel at a station equipped with another system. Criterion (ii) depends on selecting the place to bolt or screw the cylinder to the inner surface of the steel shell of the vehicle.

Pneumatic LPG Reducers (<100 kW) are usually used for the conversion of vehicles with carburettor. Electro-Assisted LPG Reducers (>100 kW) equipped with sensitivity and idling adjustments are recommended for the conversion of electronic fuel injection (Single-point injection, Continuous injection, Central port injection, Direct injection, etc.) cars. They also fit carburetted cars as well.

LPG cylinders, in cars, can be installed in a trunk, in place of a spare tyre or, if possible, under the vehicle. Depending on the place of installation LPG tanks of different sizes and two shapes (cylindrical and toroidal) are manufactured. The patterns of their installation in a car are presented in Fig. 3.

In choosing a tank according to the shape and capacity it is important to assess the additional weight and its place in a car. It is necessary to assess both the weight of an empty vessel and the weight of a fuel having in mind that the tank is filled up to 80% of its volume. As a car will have to carry an additional weight it is important to take account of its influence on the vehicle's stability. Fig. 4 presents functional comparison of the two types of gas tanks (cylindrical and toroidal) for their weight /volume ratio. The data

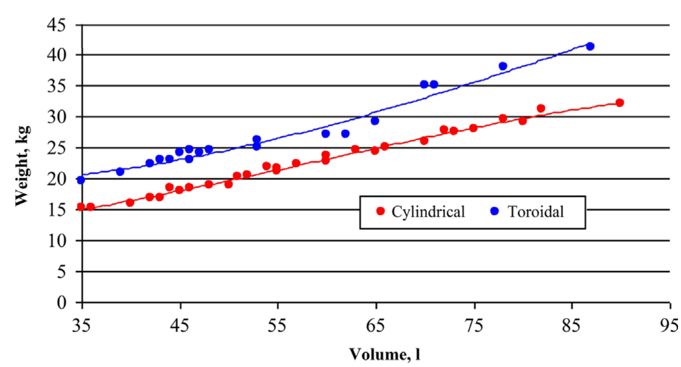

Fig. 4. Dependence of LPG tanks made in the EU member countries on capacity and shape [1].

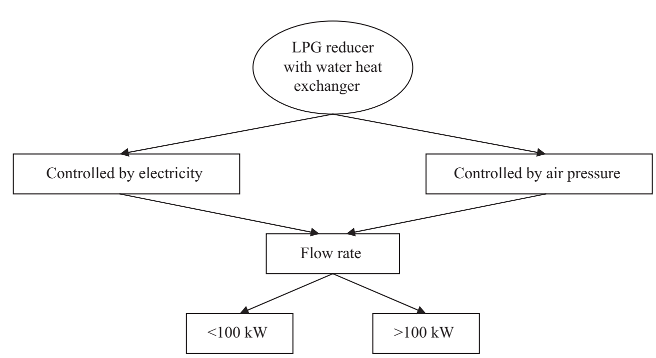

Fig. 5. Flow chart for the classification of LPG reducers with water heat exchangers [1].

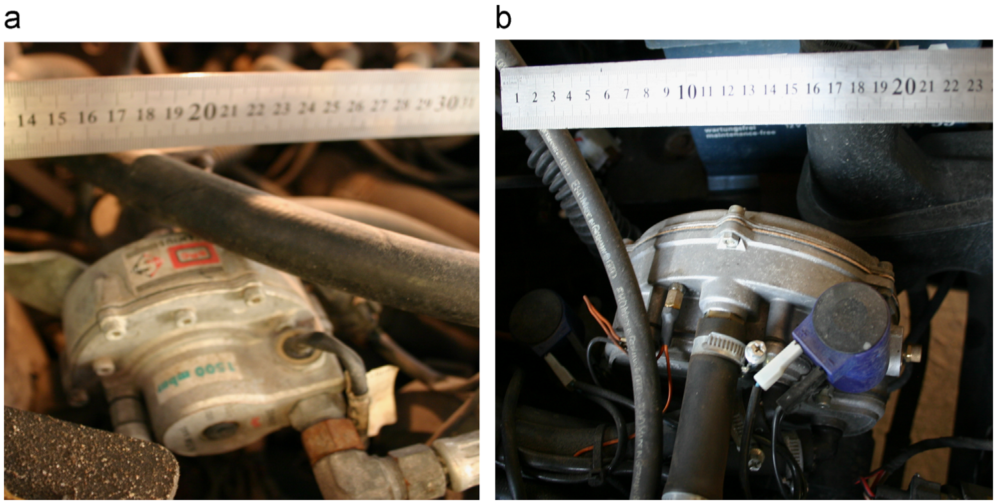

Fig. 6. LPG reducers of different systems: a—LPG vacuum reducer, b—pressure reducer for LPG with a built-in vaporization system.

presented suggests a conclusion that the toroidal tanks are about 30% heavier for the cylindrical ones having the same volume.

The initial part of an LPG preparation system is a gas reducer with water heat exchanger (Fig. 5). Its main functions - changing the liquefied state of LPG into a gaseous state and maintaining a constant temperature (provides the heat necessary for liquid LPG vaporizing). Independently from the LPG state conditions in a tank or engine load, this allows to maintain a constant pressure at the outlet. A water/gas heat exchanger can be divided according to the control method and flow rate. Their classification diagram is presented in Fig. 5.

Two main types of LPG reducers most commonly used in retrofitted vehicles in a large number of European countries over the 1992 to 2000 period [1] are presented in Fig. 6.

In a LPG vacuum reducer (see Fig. 6,a) (designed to be installed in all carburetor vehicles) gas delivery is controlled by intake manifold vacuum, or engine vacuum. As described in Ref. [34], LPG arriving through a copper tube enters the vaporization-reduction chamber of the LPG pressure reducer. Here in, LPG is vaporized and reduced in pressure. During vaporization process the LPG could reach maximum pressure of 800 kPa which later is reduced to approx. 50 kPa [34]. The pressure reduction is possible by exploiting the pressure exerted by the liquefied petroleum gas on the membrane which is connected to the lever that closes the feed orifice [34]. An alternative modification for LPG vacuum reducer is pressure reducer for liquefied petroleum gas with a built-in vaporization system (see Fig. 6,b) (for carburettor or single point injection systems). The system ensures LPG turn from its liquid form to the gaseous state, and is fitted with the electromagnetic device, which is operated by a control board, making additional gas available for easy starting. The regulator is heated using water from the engine cooling circuit. Usually, this type of reducer is applied for conversion of motor vehicles from petrol to LPG and comes in three versions: (i) for engines up to 110 kW,
(ii) for engines up to 150 kW, and (iii) for engines turbo up to 150 kW.

Most of the gasoline-powered ICE cars use one of two basic types of fuel delivery systems: carbureted system (in older cars) that uses a mechanical fuel pump, and fuel-injected system that uses an electric or electro-mechanical fuel pump (in newer cars). Each different type of fuel delivery system has its own benefits, limitations, and potential applications. By comparing them it is easier to see the differences. Table 3 shows the different variations of petrol delivery systems, starting with the carburettor (device that blends air and fuel for an ICE) and finishing with petrol direct injection.

The systems of fuel delivery can be classified according to their control principles (Fig. 7). The use of mechanically fixed gas flow rate throttle without active regulation can be characterized as the simplest method of fuel delivery. The main parameter describing it is a mechanically set throttle with no active regulation which regulates the gas flow rates.

The throttle regulating gas flow rate can be controlled by two ways: using the vacuum created in the flammable mixture delivery system of an IC engine or using the electronic throttle control. With vacuum regulation the position of a throttle depends only on the pressure in an IC engine's intake manifold. The electronic throttle control assesses the signals from the sensors of a reducer with water/gas heat exchanger's temperature, composition of exhaust gases and the position of the accelerator pedal.

4. Analysis of operation of ICEs using LPG

The majority of the engines run on fuel gas are not specially designed to operate using this particular type of fuel – they are just retrofitted from Otto or Diesel engines. Usually cars have retrofitted Otto engines which can use both types of fuel: LPG and petrol. In the case of heavy duty vehicles the retrofitting is based on positive properties of fuel gas. Most often the retrofitting engines of heavy duty vehicles are diesel ones [54,55]. Three possible ways to use LPG as a fuel for heavy duty vehicles are as follows:

- Replacement of a diesel engine with a gas engine;
- Installation of a LPG delivery system (the main fuel delivery system of the vehicle remains unchanged);
- Complete retrofit of a diesel engine to run entirely on a fuel gas.

The second way could be named as an intermediate design solution. Its peculiarity is that in diesel engines gas fuel is delivered to an intake manifold and after having been mixed with air it passes to cylinders; at the same time diesel fuel is also used – only a lesser amount of it is injected into the cylinders [1]. This method is chosen in order to improve fuel economy and to reduce exhaust emissions. Though this retrofitting method is the simplest one, it does not allow the benefits of all gas engine advantages.

The third method is the most popular as the retrofitting of an original ICE instead of replacing it by a special gas engine helps to avoid additional design difficulties: it is not necessary to adjust new engine with the agearbox (including the necessary adjustment of the

Table 3
Variations of petrol delivery systems and their compatibility with LPG delivery systems.

Fuel Delivery Method	Benefits	Limitations	Compatibility with LPG delivery systems
I. Carbureted system			
Carburettor	• Petrol mixture can be freely adjusted.	• Most inefficient system (the problem is turning a liquid into a gas in a way that it's controlled); • Hard to adjust for economical operation [1,19].	• Single point (or mixer) open loop systems (the simplest and oldest design). The open loop system is not "intelligent", it cannot adjust the fuel /air mixture ratio according to any information available apart from its fixed settings; • Open loop systems are suitable for most cars up to 1992 • Oxygen sensor (or lambda sensor) does not required; • A fuel changeover switch of petrol-to-LPG or LPG-to-petrol is fitted inside the vehicle.
II. Fuel-injected system			
Single-port fuel injection ("wet manifold system")	• Better control of petrol delivery; • More precise fuel atomization	• Fuel injector still dumps gasoline (a mixture of gas and air usually coalesced into fat droplets) into intake and relies on air induction for delivery; • Only slightly improves emissions.	• Single point (or mixer) closed loop type systems (designed for early electronic and mechanical fuel injection engines). It is actually an Open loop system having a variable mixture control; • Suitable for most cars up to 1996; • Oxygen sensor and Catalytic Converter are mandatory;
Multi-port fuel injection	• Delivers petrol (pressurized and atomized charge of fuel) directly to each cylinder right at the intake valve [1]; • Improves efficiency (charge of fuel can be regulated by the injection system through the built-in computer processor); • Reduces CO_2 emissions [9].	• Some fuel remains unburned and collects carbon in intake and on valves [53].	• Multipoint non sequential systems; • Suitable for all cars 1992–1999 having Oxygen sensor, Catalytic Converter and plastic inlet manifold; • Suitable for all Turbocharged and Supercharged engines.
Direct fuel injection	• Delivers petrol directly to cylinder combustion chamber for maximum efficiency and minimal emissions.	• Repair costs generally higher than single- and multi-port fuel injection [1].	• LPG is injected into the combustion chamber (as opposed to fuel and air mixing before the intake valve); • Suitable for vast majority of electronically controlled fuel injected cars having Oxygen sensor, Catalytic Converter and plastic inlet manifold; • Suitable for all Turbocharged and Supercharged engines.

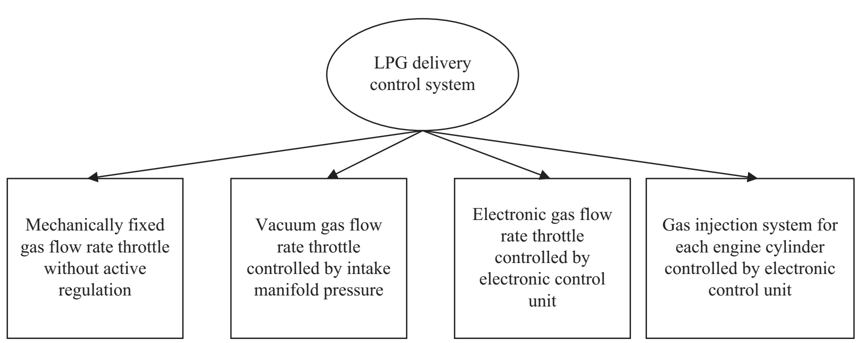

Fig. 7. Flow chart for the classification of LPG delivery control systems [1].

fixing places, etc.) and the clutch. When heavy duty diesel engines are retrofitted it is expected to ensure functional longevity and the prolongation of the period between technical maintenance, however, a problem of increased energy consumption emerges and one of the reasons for that is an additional weight of the equipment. In order to increase the efficiency of engines run on fuel gas the following measures are taken [1]:

- Increase in mean effective pressure;
- Leaning of the fuel mixture (due to slower burn rates);
- Increase in compression ratio;
- Application of variable valve timing;
- The use of direct fuel injection.

Fuel delivery systems in Otto engines are developing fast. The purpose is to reduce fuel consumption and increase engine power output at the same time as well as to minimize environmental pollution [2,56–62]. The variation and diversity of petrol delivery systems determine design variations of LPG delivery systems correspondingly. The main factors influencing the differences of

the processes in internal combustion engines running on LPG and petrol can be singled out [1]:

- Intake system configuration;
- Compression ratio;
- Ignition timing;
- Temperature and the relative humidity of the ambient (intake) air;
- Intake air pressure.

One of the problems with petrol engines is the difficulties of even distribution of fuel in multi-cylinder engines, which is solved by changing the shape of intake manifolds, developing fuel-mixture formation systems and specifying their control algorithms [63,64]. The main purpose of using LPG effectively is the minimal change in fuel consumption after the fuel type has been changed. The application of this criterion often results in the formation of the fuel-air mixture which is often too lean within the higher ranges of engine's rotational speed and this is especially felt when using the gas equipment of older (1st, 2nd) generations. The IC engines running on very lean mixtures can demonstrate the difficulties of ignition, flame extinction and incomplete combustion process [64–72] and these are the main causes for the huge increase in levels of emissions.

Consumers often replay debates over the fact that petrol engines have developed maturely and new technologies emerge from different manufacturers to improve their performance with low fuel consumption; and discuss the advantages of LPG over modern petrol engines. It should be noted that spark-ignition engines fueled by LPG has slightly decreased on power output up to approx. 3–4% compared to unleaded petrol (ULP) [37]. It is mainly affected by the lower flame speed of LPG if compared to ULP Also, ICE engine fueled by LPG reduce on specific fuel consumption (SFC) to approx. 28% [37]. Although, 60% propane-40% butane mix has higher heating value (see Table 2) than gasoline (approx. 43.448 MJ/kg), it produces lower brake mean effective pressure (bmep) values compared to gasoline. This reduction can be attributed to lower energy density of fuel-air mixture due to their higher stoichiomteric air-fuel ratio. The slower burning rate of LPG (see Table 2) can be considered as another reason of lower bmep. Specific fuel consumption (SFC) is the scale to measure the efficiency or economy of the fuel to the internal combustion engine. Sulaiman et al. [37] concluded that LPG-fueled engine has less SFC as compared to ULP-fueled engine by up to approx. 28%. Additionally, LPG-powered engine has lower energy price than unleaded petrol-powered engine with difference up to approx. 31–47% [37].

5. Structural control diagrams of gas delivery systems

According to the classification of LPG delivery systems described in Chapter 3 and analyzing the equipment of various generation (the 1st, 2nd, 3rd, 4th, and 5th) we can make a conclusion that the main factor influencing the quality of system performance is the amount of information on the parameters of an engine in operation transferred to the control unit of an LPG delivery system. Therefore, in performing the analysis of LPG fuel systems for ICEs, investigation must also pass a thorough examination of their structural control diagrams. While picking out the sources of information supply to an LPG control unit in these diagrams it is possible to create a general diagram of system selection for a certain IC engine.

The mechanically controlled LPG carburetion systems (first generation) are characterized by the fact that the operation of the system depends only on the initial parameters of adjustment

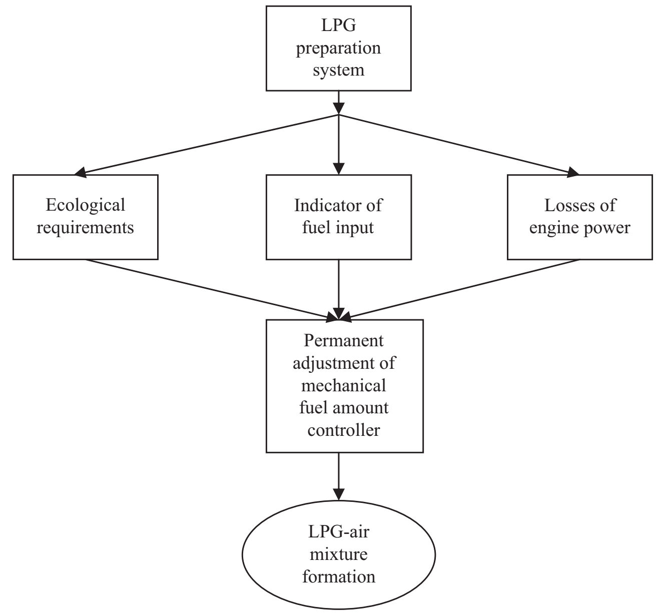

Fig. 8. The diagramt of LPG delivery control system of the first generation [1].

(Fig. 8). In each case of the system adjustment the greatest influence is made by the human factor as there are no methodologies created for the performance tuning and the system itself is most often adjusted according to the criteria defined by a user. We distinguished three main requirements set forth by users to LPG fuel delivery systems [1]

- Ecological;
- Fuel consumption;
- Engine power.

LPG flows through the main low-pressure fuel line to a valve (for lean adjustment) inside the carburetor. There is a bolt on the back of the carburetor to adjust it. Depending on how far in and out Automotive service technician turn the bolt, it opens and closes, respectively. Hanging from the top inside of the air/fuel blending device is a diaphragm connected to a steel plunger that goes down into the LPG port. As vacuum increases, this diaphragm opens further and pulls the plunger off of the LPG port letting more fuel in. The shape of the plunger is the main determining characteristic to affect carburetor performance (to get maximum engine power, fuel economy, and improved ecological characteristics).

In adjusting the LPG delivery system of the second generation (intended to use in SI engines with single and multipoint fuel injection, catalyser and lambda sensor) the main adjustment parameter is ecological requirements as the system can vary the amount of LPG. The gas fuel is still fed at the beginning of the intake system, i.e. centrally, before the throttle. The LPG amount depends on the pressure in an intake manifold (Fig. 9). Most commonly the 2nd generation system is adjusted on IC engine idle according to the ecological requirements set forth for a car. The pressure in the intake manifold as a system control parameter in its turn depends on a throttle valve opening angle and on a geometrical shape of the intake manifold. Thus, the algorithm of the LPG system control of the 2nd LPG system control depends on the initial adjustment of the system however the design features of an engine are assessed as well.

Along with 2nd generation systems first maintenance and calibration software was introduced. It was possible to display and manipulate basic working parameters of the system and the engine, including lambda sensor.

In assessing the gas equipment of the third generation (constant gaseous stage LPG injection when gas fuel is fed into individual lines of the intake manifold, near the valves) the engine manufacturing data are entered into an LPG control unit (Fig. 10).

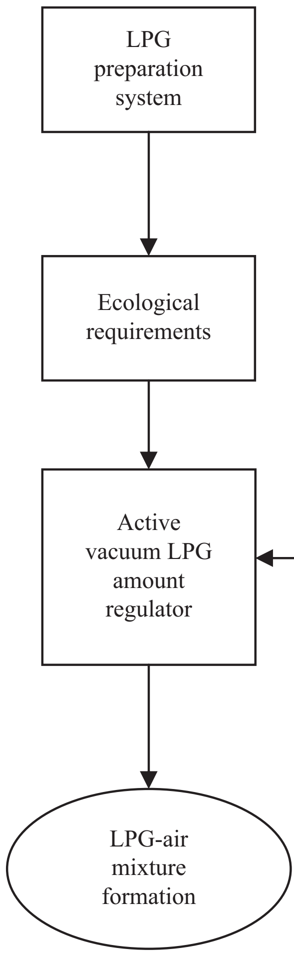

Fig. 9. The diagram of LPG delivery control system of the second generation [1].

While programming the control unit there is a possibility provided for the attribution of desirable values of the required parameters to the corresponding LPG amount values, however, there are no specific methods for such an adjustment, – it depends solely on the human factor, i.e. experience and qualifications of the person performing the equipment adjustment and testing.

It is worth to be mentioned that the control algorithm set by a manufacturer is based on the analysis of the exhaust gas composition, i.e. the criterion of ecological parameters. Therefore, the LPG systems of this type are also called EKO systems. Depending on the manufacturer of the gas equipment additional functions are available, e.g. limitation of maximum revolutions, programmable switching of fuel type and a self-diagnostic function.

The main design advantage of the gas equipment of the fourth generation (sequential gaseous stage LPG injection) is related with the section of air-fuel mixture formation. These are applied for SI engines equipped with multipoint fuel injection (with on-board diagnostic (OBD) system, lambda sensor, catalytic converter) [1,73]. In this system the gas is injected in the intake manifold separately for each cylinder at a certain distance from an intake valve, which depends on the design of an engine.

The system control unit (Fig. 11) processes information by analogy to a petrol delivery control unit. The manufacturers of the equipment of the fourth generation set a basic control algorithm which is simply adapted for an individual IC engine according to the following methodology:

- All data received by the LPG control unit are transferred to the external programming device, when the engine runs on petrol;
- The data received is processed and transferred to the LPG control unit;
- The operating parameters of ICE running on LPG are constantly checked during vehicle driving.

Fifth generation systems with sequential liquid stage LPG injection are dedicated for SI engines (with multipoint fuel injection, on-board diagnostic (OBD) system, lambda sensor, catalytic converter), are operated and controlled like their fourth generation counterparts as well as analyze the signals from petrol injectors [73]. Unlike in 1st–4th generation systems, LPG is fed into the ICE in its liquid form, without vaporizing, and the LPG injection

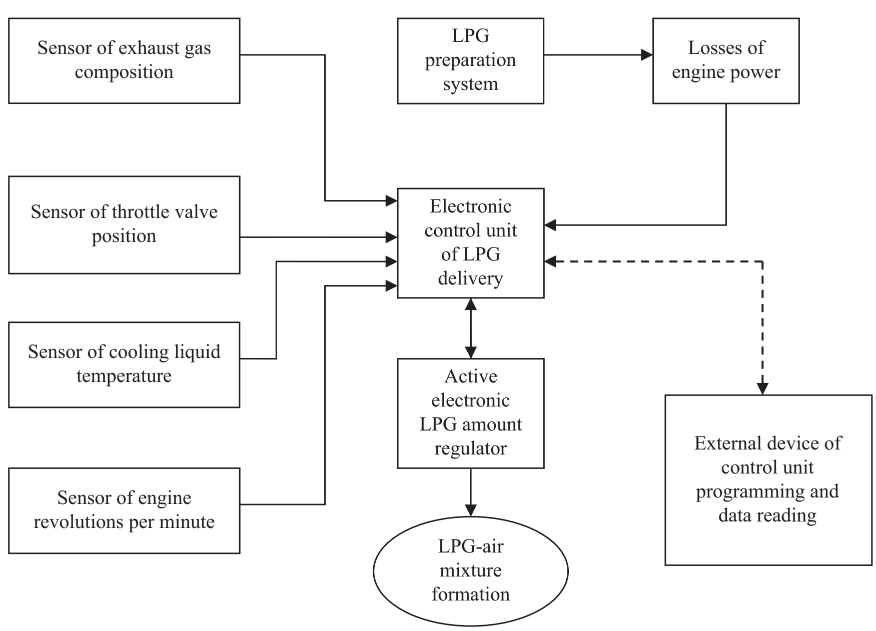

Fig. 10. The diagram of LPG delivery control system of the third generation [1].

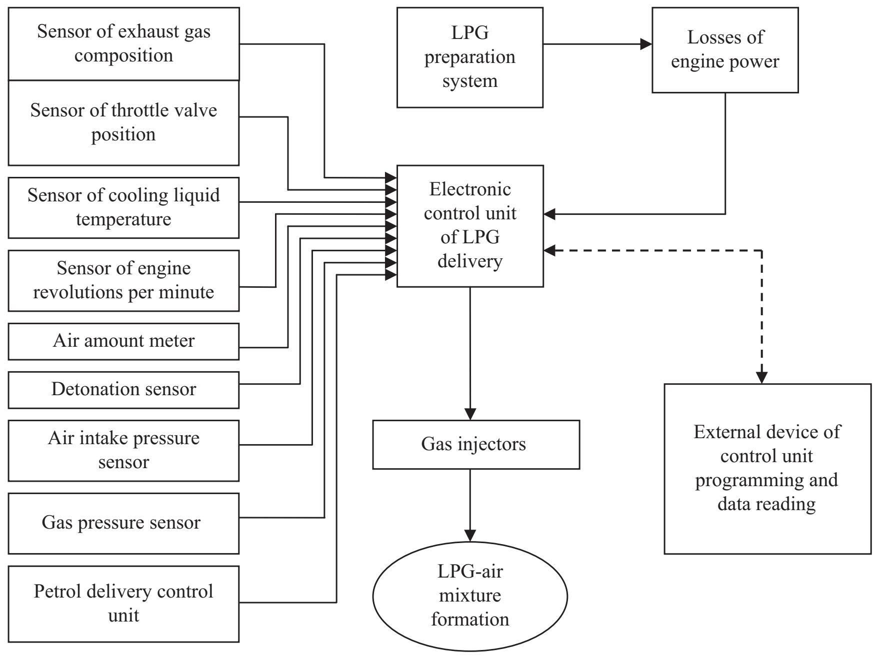

Fig. 11. The diagram of LPG delivery control system of the fourth generation [1].

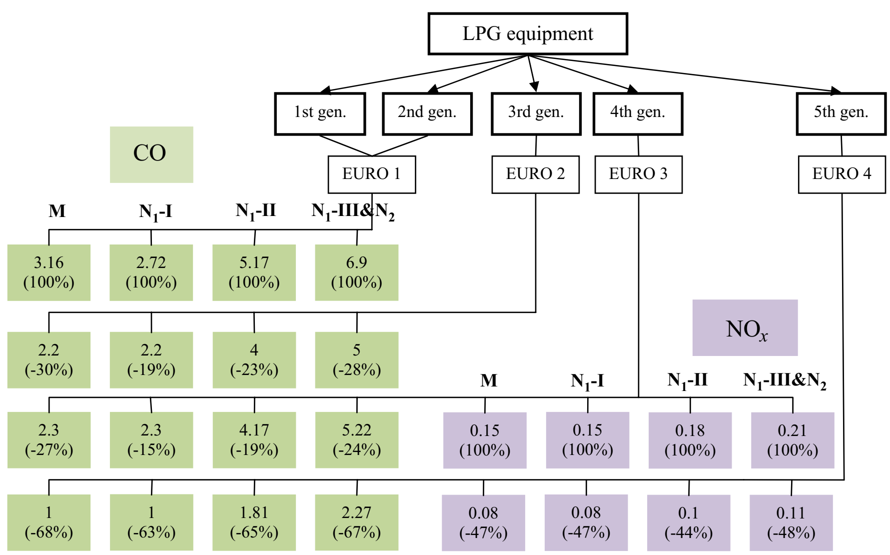

Fig. 12. Different generation LPG equipment's compliance with European CO and NO_x emission standards for Petrol (Gasoline)-powered passenger cars (Category M) and light commercial vehicles ($\leq$ 1305 kg (Category N1-I), 1305–1760 kg (Category N1-II), and $>$ 1760 kg max 3500 kg (Category N1-III & N2))g/km.

time is calculated on the basis of petrol injection times. The main advantages of the 5th generation system are ease of conversion coupled with the very precise fuel dosage [73]. Among the disadvantages are limited applicability and high price for retrofit works [73].

6. Conclusion

The assessment of existing LPG systems fitted to conventional vehicles with a special emphasis on their structural control diagrams as the key point was carried out. These findings are intended to narrow the existed gap of information on the existing management algorithms for LPG equipment and are primarily devoted to the scholars working in the broadly defined field of automotive engineering and its respective subsystem – fuel economy/emissions engineering. The wider introduction of different knowledge on LPG application in the transport sector can give a positive boost to the future studies and lead to successful outcomes in sustainability plans and actions demand in many countries.

Numerous data gaps were revealed during this study. There was:

- The update on future trends in the automotive industry (diesel cars in Europe starting a long slow decline and petrol cars regaining lost ground). In paralel, we discuss LPG alternative to petroleum as a medium-term perspective in the transition to sustainable fuels and transport, if this trend become a reality;
- Typical performance and cost figures for retrofit LPG/CNG/LNG cars;
- Differences in vehicular petrol delivery systems and their compatibility with LPG delivery systems;

- Structural control diagrams of LPG delivery systems, their advantages and limitations.

We draw the final conclusion that relatively low GHG emissions from 4th–5th generation LPG equipment-driven vehicles when compared with 1st–3rd generation LPG equipment's performance in passenger cars and light commercial vehicles of different categories (see Fig. 12) appears to arise from the present maturity of LPG equipment's control algorithms. Finally, the graphical abstract is provided to familiarize readers with the effect of each of those systems on engine performance (see Fig. 12) which is in compliance with legal requirements set out by Euro 1, Euro 2, Euro 3, and Euro 4 standards.

All 5 different types of LPG equipment have their own advantages and limitations. Some key benefits can be listed: the function of automatic switch from gas to petrol (3rd and 4th generation); possibility of starting the vehicle on gas at any temperature (no need to evaporate it by heating), no power loss, no higher consumption rate (5th generation). Among the drawbacks are not advanced response times for mixture adjustments (3rd generation); high complexity of the whole system, low repairability, larger repair costs, and high sensitivity to LPG's contaminants (CO_2, H_2S, mercaptans, elemental sulfur, etc) (5th generation).

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